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# RESEARCH MEMORANDUM

## CYCLIC ENGINE TEST OF CAST VITALLIUM TURBINE BUCKETS - I

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# CYCLIC ENGINE TEST OF CAST VITALLIUM TURBINE BUCKETS - I

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## SUMMARY

An investigation was conducted to correlate the engine service performance of cast Vitallium turbine buckets with standard laboratory metallurgical data. Data were obtained from four turbine wheels of Timken alloy with cast Vitallium buckets. In order to accelerate bucket deterioration, the turbine wheels were subjected to 20-minute cycles consisting of 5 minutes at idle and 15 minutes at rated speed.

A bucket broke on the first wheel during cycle 22 after 7 hours and 20 minutes. The broken bucket was replaced and during the third cycle after the replacement a second bucket broke after a total running time of 8 hours and 12 minutes. The first bucket failure on the second wheel occurred during cycle 29 after 9 hours and 28 minutes; no further failure occurred during 66 additional cycles. Total running time on this wheel was 31 hours and 40 minutes. The third wheel was run for 229 cycles (76 hr and 20 min, total running time) without a failure. The fourth wheel was operated for 105 cycles (35 hr, total running time) without a failure. Examination of the broken buckets indicated that the failures were probably due to fatigue. Massive eutectic areas that existed near the trailing edge probably contributed to the low fatigue strength.

## INTRODUCTION

As part of a general evaluation of various heat-resisting alloys for jet-engine and gas-turbine application, investigations were made on four Timken-alloy turbine wheels with cast Vitallium buckets in order to correlate the performance in actual engine operation with standard metallurgical laboratory tests.

Each of the turbine wheels was run through the same cyclic engine test. The cyclic type of test was chosen so that the turbine buckets would be subjected to a greater thermal shock than would be encountered in normal operation and so that the time necessary for a bucket to fail would be reduced.

Cast Vitallium buckets of the current production type were investigated in order to have a basis for the evaluation of materials that have not been previously used in this application.

Chemical analysis and metallurgical examinations were made on the broken and unbroken buckets and measurements to determine the turbine-bucket elongation were taken during the inspection periods. The temperature of the material in the leading edge of turbine-nozzle blades was measured at several rotor speeds.

## APPARATUS

The investigation of the four Timken-alloy turbine wheels with cast Vitallium buckets was conducted on several turbojet engines mounted on a pendulum-type sea-level test stand, as shown in figure 1. The turbojet engines, which incorporate a dual-entry centrifugal compressor, 14 combustion chambers, and a single-stage turbine, have a thrust rating of 4000 pounds.

The fuel used was AN-F-32. Rotor speed was measured by a chronometric tachometer. Gas temperature was measured at the exhaust-cone outlet by 14 unshielded chromel-alumel thermocouples equally spaced about the circumference and extending radially 2 inches into the tail pipe. The gas temperature at the exhaust-cone outlet was controlled by an NACA variable-area jet nozzle (fig. 1).

Turbine-bucket failures were detected by means of a Sperry-M.I.T. linear-vibration pickup unit mounted on the accessory case of the engine and connected to an electronic voltmeter. An attempt was made to determine the change in the turbine-wheel radius and the bucket elongation due to engine operation. The method used to measure the radius of the turbine wheel was not sufficiently accurate to determine the small changes in the turbine-wheel dimensions. The fixture used to obtain the change in position of the bucket tips (fig. 2) gave very satisfactory results. The change in position of the bucket tips, which is presented as turbine-bucket elongation, is actually the bucket elongation plus the change in the wheel radius.

The four turbine wheels investigated were of Timken alloy, forged according to standard practice, with cast Vitallium buckets. Wheel assemblies 1, 2, and 4 were made by one manufacturer and wheel assembly 3 was made by another.

## PROCEDURE

### Cyclic Engine Test

For each test, an engine was assembled with one of the four wheels and mounted in the test cell. The turbine-wheel radius and the bucket lengths were measured before the engine was run.

During the starting period, the gas temperature at the exhaust-cone outlet was held at or below 1800° F. The engine was operated at a rotor speed of 6000 rpm to check the condition of the engine before starting the cyclic runs each day. After the engine check was obtained, the engine was subjected to 20-minute cycles consisting of 5 minutes at idle and 15 minutes at rated speed. The allowable variation in rotor speed and exhaust-cone-outlet temperature is presented in the following table:

| Duration (min) | Duration (sec) | Rotor speed (rpm) | Gas temperature at exhaust-cone outlet (°F) |
|---|---|---|---|
| 5 | 0 | 3500±50 | 1110 maximum |
| 0 | 15 | Acceleration to 11,500 | 1450±50 |
| 15 | 0 | 11,500±50 | 1240±20 |
| 0 | 15 | Deceleration to 3500 | 1240 maximum |

The sequence of operation listed in the table constitutes one cycle. After a five-cycle run, the engine was shut down and a visual inspection of the turbine was made without removal of the tail pipe. After each 15 cycles, the exhaust cone was removed and the turbine-wheel radius and the bucket lengths were measured. The wheel and the buckets were inspected by the Zyglo process and the entire engine was visually inspected.

After the first turbine-bucket failure on a wheel, the extent of the damage to the remaining buckets was carefully noted in order to be certain that subsequent bucket failures were not caused by nicks from a previous failure. The bucket failures mentioned damaged the tips of the remaining buckets but none of the buckets were nicked on either the leading or the trailing edges in the area where subsequent failures occurred.

## Metallurgical Examination

Identification. - The buckets to be examined were identified by assigning to each the number of the wheel and a number indicating its relative position on the wheel. For example, bucket 13 on wheel 1 is designated bucket 1-13.

Visual examination. - The broken buckets were examined visually and under a low-power microscope before they were sectioned for further analysis.

Macroexamination. - The buckets were electrolytically etched in 10-percent hydrochloric acid to show the grain size. End and side views of the broken edges are shown in figures 3 and 4, respectively.

Chemical analysis. - Half of the dovetail section of each bucket examined was cut off with an abrasive wheel and chips were removed from each. These chips were then analyzed by a commercial laboratory. The analysis of molybdenum content presented was made by the National Bureau of Standards.

Microexamination. - Two samples were cut from both the leading and the trailing edges of the broken buckets. The locations from which the samples were taken are shown in figure 5. The samples were polished and electrolytically etched in hydrochloric acid.

X-ray examination. - Glancing photographs of the cracks were taken with a 225-millimeter camera using a collimating slit, an iron tube, and a manganese filter.

## RESULTS AND DISCUSSION

Cyclic engine tests were made on four turbine wheels with cast Vitallium buckets. Metallurgical examinations were made on the broken buckets to determine the cause of the failures.

## Engine Test

Wheel 1. - Wheel 1 was installed in an engine and was run-in by the engine manufacturer prior to the tests at the Cleveland laboratory. The first failure on wheel 1 occurred during cycle 22 after 7 hours and 20 minutes. The broken bucket (bucket 1-13), shown in figure 6, was replaced, the wheel rebalanced, and the runs continued. Bucket 1-2 failed three cycles later during cycle 25 after a total running time of 8 hours and 12 minutes (fig. 7). Buckets 1-12 and 1-14 were removed for comparison with the broken buckets.

Wheel 2. - Wheel 2 had not been run prior to this investigation. The first bucket failure on wheel 2 (bucket 2-18) occurred in cycle 29 after 9 hours and 28 minutes (fig. 8). The broken bucket was replaced, the wheel rebalanced, and the run continued. After 95 cycles (31 hr, 40 min total running time), the test was stopped to repair the rear-compressor-inlet guide vanes and the ring-and-tube assembly.

Wheel 3. - Wheel 3 had been run-in by the engine manufacturer and had been operated 36 minutes by the Army Air Forces prior to the investigation at this laboratory.

After 11 hours and 8 minutes, the ring-and-tube assembly was found to be so badly damaged that the engine could not be run. The damage sustained by one of the outer flame tubes is shown in figure 9. Operation was resumed after the ring-and-tube assembly had been replaced. An inspection after a total running time of 28 hours and 44 minutes showed that the nozzle diaphragm had been badly eroded (fig. 10) and that the stiffeners on the compressor cover plate were cracked.

The turbine wheel was therefore removed, installed in another engine, and the running resumed. After cycle 229 (76 hr, 20 min total running time), the nozzle diaphragm was again found to be in bad condition and the engine was removed from the test cell for overhaul. No bucket failure had occurred. Many of the buckets had shifted in the axial direction, six of them sufficiently to rub on the gas baffle in the exhaust cone (fig. 11). Two buckets (buckets 3-16 and 3-43) were removed from wheel 3 for comparison with the broken buckets from the other wheels.

Wheel 4. - Wheel 4 had not been run prior to this investigation. This wheel was run to obtain a check on the results obtained from wheel 2. No bucket failure occurred, however, in 105 cycles (35 hr total running time).

Summary of bucket failures. - The results of the engine tests are summarized in the following table:

| Wheel | Running previous to cyclic test | First bucket failure | | | | Second bucket failure | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Cycles | Total running time | | Bucket | Cycles | Total running time | | Bucket |
| | | | (hr) | (min) | | | (hr) | (min) | |
| 1 | Run-in by manufacturer | 22 | 7 | 20 | 13 | 25 | 8 | 12 | 2 |
| 2 | None | 29 | 9 | 28 | 18 | 95 | 31 | 40 | (a) |
| 3 | Run-in by manufacturer plus 36 min by AAF | 229 | 76 | 20 | (a) | | | | |
| 4 | None | 105 | 35 | 0 | (a) | | | | |

[a]No failure.

Turbine-bucket elongation. - The elongation of the turbine buckets for the four wheels is plotted in figure 12; the bucket failures are also indicated. The first bucket failures on wheels 1 and 2 so damaged the tips of all the other buckets that further measurements could not be made. The elongation data on wheels 3 and 4 are more complete; no bucket failures, however, have yet occurred on these wheels. All failures occurred at about the same distance from the bucket roots and the type of failure was the same in all cases (fig. 13).

Nozzle-blade temperature. - The temperature variation along the leading edge of a turbine-nozzle blade located directly behind burner 1 is shown in figure 14. These temperatures were obtained by three chromel-alumel thermocouples located as shown in figure 14. The location of a thermocouple $2\frac{1}{2}$ inches from the inner spacer ring was chosen because in previous nozzle-blade failures most of the cracks were near this position. The data indicate that the hottest portion of the nozzle blade is about $2\frac{1}{2}$ inches from the inner spacer ring. The fractures on the trailing edge of the turbine buckets are approximately $2\frac{1}{2}$ inches from the root. Because the turbine-nozzle blades and the turbine buckets are supported in a different manner, the temperature distribution in them may not be the same; the bucket failures occurred, however, at the same radial location as the maximum measured nozzle-blade temperature.

## Metallurgical Examination

Nature of failure. - Because one of the purposes of this program is to correlate service performance with the properties of various alloys as determined in standard laboratory tests, it is important to be able to identify the nature of the mechanism that causes failure. Such an identification would permit an appraisal of the relative importance of the properties of a material as determined by creep, stress-rupture, or fatigue tests. Examination of the broken buckets discloses that:

1. The appearance of the failure is the same in all samples.

2. The fracture exhibits two definite zones, which are quite different in appearance. From the trailing edge to about the middle of the bucket, the fracture has a conchoidal surface similar to those of fractures obtained in the failure of brittle materials. This part of the fracture is referred to as the "brittle" fracture. The brittle fracture has a dark gray coat of oxide. The rest of the crack has a fibrous appearance very similar to that exhibited by tensile-test specimens that have failed with a cup-and-cone fracture. This portion of the fracture is referred to as the "ductile" fracture. The ductile fracture has a bright blue oxide coating.

3. Micrographic examination makes it almost certain that both types of failure are transcrystalline.

4. A light electrolytic etch in hydrochloric acid removes the bright blue oxide coating but does not completely remove the dark gray one. This difference indicates that the oxide coating is thicker on the brittle fracture and therefore that this portion has been exposed to the air longer.

These observations lead to the conclusion that the failures are due to fatigue cracks that start at the trailing edge and progress until the centrifugal-force stress on the remaining portion of the blade becomes equal to the ultimate strength and the material fails in tension. Specimens that have failed in stress-rupture tests of long duration (that is, of low stress) exhibit this type of brittle failure; however, the cracks present in such failures are intercrystalline and not transcrystalline.

Because such a variation exists between the life of buckets obtained from two sources, a metallurgical examination was made to find the reason for the short life of the broken parts.

The chemical analysis of the broken and unbroken buckets presented in table I indicates that they were within the engine manufacturer's specifications.

The macroexamination did not disclose any significant differences either between the three samples or between broken and unbroken buckets from the same wheel. The grains at the trailing edge were much smaller than in the body of the bucket probably due to variation in the cooling rate in the mold. (See fig. 3.)

Badger (reference 1) mentions that the early Vitallium alloys exhibited brittleness within the temperature range between 1300° and 1475° F due to aging. The phase precipitating from the matrix had a close-packed hexagonal structure. The brittleness was eliminated later by addition of nickel. In order to ascertain if any embrittlement of this nature had taken place, X-ray diffraction pictures were made of the broken parts. Although no lines peculiar to a close-packed hexagonal structure were detected, the results were not conclusive because the large grain size prevented satisfactory patterns from being obtained.

Readings of superficial hardness indicated no abnormal increase in the hardness of the broken buckets. The material therefore cannot be considered as having been embrittled as a result of phase changes.

Microscopic investigation did not definitely establish the cause of the bucket failures. Well-defined eutectic areas at the dendtritic boundaries and some carbide precipitation existed (fig. 15). These eutectic areas (figs. 16 and 17) are very prominent at the trailing edge, where it is believed the crack started. A view of a comparable area at the leading edge (fig. 18) shows a small amount of eutectic material. Such a concentration of eutectic areas at the trailing edges may be a factor contributing to the start of fatigue cracks.

## SUMMARY OF RESULTS

The results of the cyclic engine tests and of the examination of the three broken cast Vitallium turbine buckets may be summarized as follows:

1. The first wheel run sustained a bucket failure during cycle 22 after 7 hours and 20 minutes. The broken bucket was replaced and three cycles later another bucket failed after a total running time of 8 hours and 12 minutes.

2. The second wheel had a bucket failure during cycle 29 after 9 hours and 28 minutes. No further failure occurred in 66 additional cycles during a total running time of 31 hours, 40 minutes.

3. The third wheel was operated 229 cycles (76 hr and 20 min) without a bucket failure.

4. The fourth wheel was run 105 cycles (35 hr) without a bucket failure.

5. Fatigue was apparently the cause of the bucket failures.

6. Massive eutectic areas that existed near the trailing edge probably contributed to the low fatigue strength.

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National Advisory Committee for Aeronautics,
Cleveland, Ohio.

## REFERENCE

1. Badger, F. S.: Metallurgy of High-Temperature Alloys. Annual Meeting A.S.T.M., June 1946.

TABLE I - CHEMICAL ANALYSIS OF SAMPLES OF CAST VITALLIUM TURBINE BUCKETS

[Molybdenum analysis by National Bureau of Standards; other analyses by a commercial laboratory]

| Element | Broken buckets (percent) | | | Unbroken buckets (percent) | | | Engine manufacturer's specification (percent) |
|---|---|---|---|---|---|---|---|
| | Bucket 2-18 | Bucket 1-13 | Bucket 1-2 | Bucket 1-12 | Bucket 3-43 | Bucket 4-16 | |
| Carbon | 0.32 | 0.29 | 0.33 | 0.250 | 0.235 | 0.231 | 0.15-0.35 |
| Manganese | .31 | .33 | .25 | .61 | .31 | .49 | |
| Phosphorus | .031 | .029 | .026 | .014 | .020 | .020 | |
| Sulphur | .05 | .05 | .05 | .029 | .024 | .024 | |
| Silicon | .51 | .57 | .53 | .52 | .49 | .41 | |
| Chromium | 27.95 | 27.78 | 27.96 | 28.40 | 28.34 | 28.16 | 25.5-29.5 |
| Nickel | 2.81 | 2.66 | 3.04 | 2.31 | 2.15 | 2.27 | 1.75-3.25 |
| Molybdenum | 5.60 | 5.85 | 5.80 | 5.80 | 5.21 | 5.60 | 5.0-6.0 |
| Cobalt | 63.37 | 63.90 | 63.92 | 62.69 | 62.85 | 62.73 | Remainder |
| Titanium | .01 | .01 | .01 | ------ | ------ | ------ | |
| Columbium | .19 | .19 | .16 | ------ | ------ | ------ | |
| Tungsten | .16 | .08 | .08 | ------ | ------ | ------ | |
| Iron | 1.06 | .75 | .49 | ------ | ------ | ------ | 0.50-2.0 |
| Copper | ------ | ------ | ------ | ------ | ------ | ------ | |
| Nitrogen | ------ | ------ | ------ | .09 | .12 | .13 | |

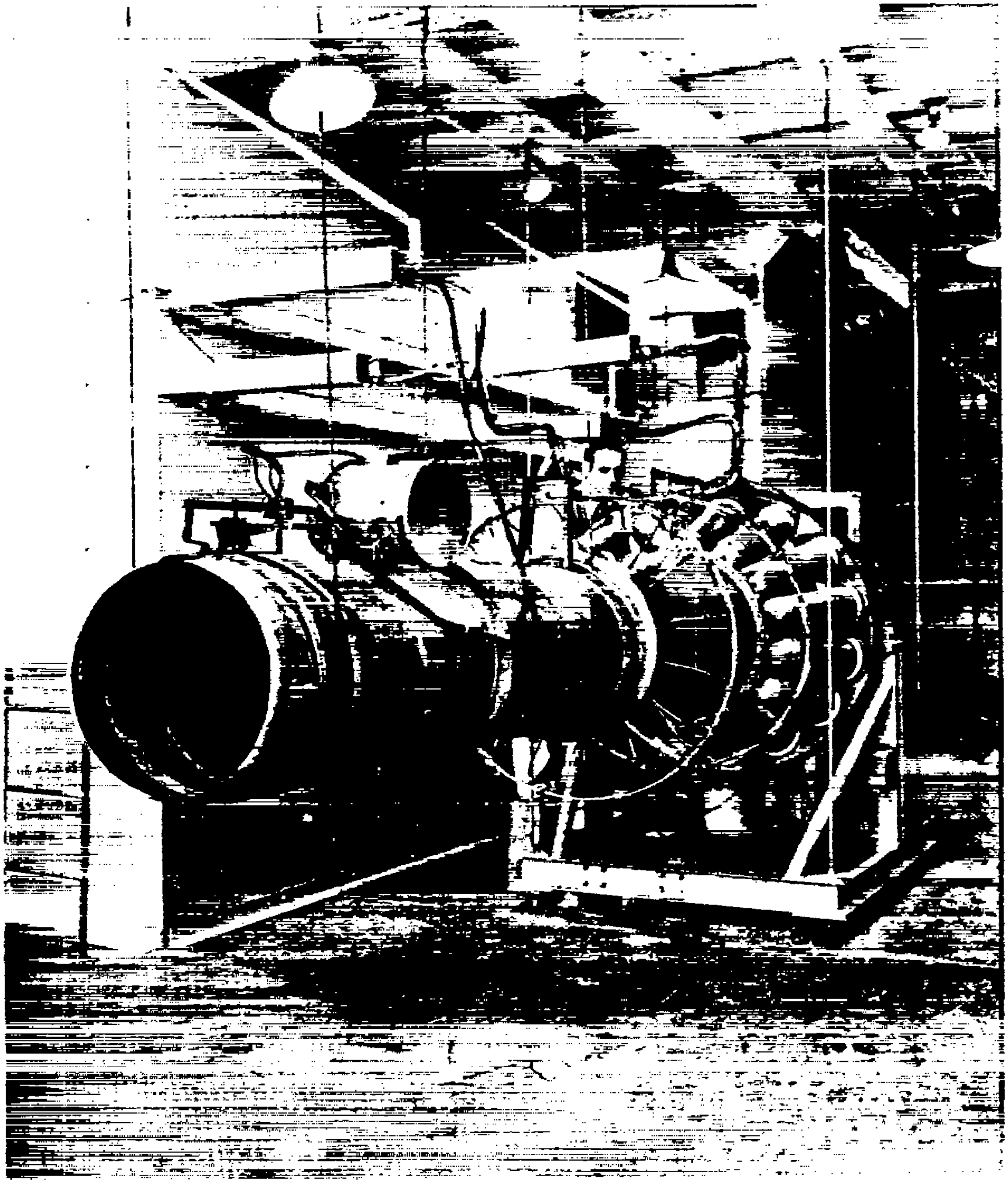

Figure 1. - Photograph of turbojet engine mounted on pendulum-type sea-level test stand showing NACA variable-area jet nozzle used to control gas temperature in exhaust cone.

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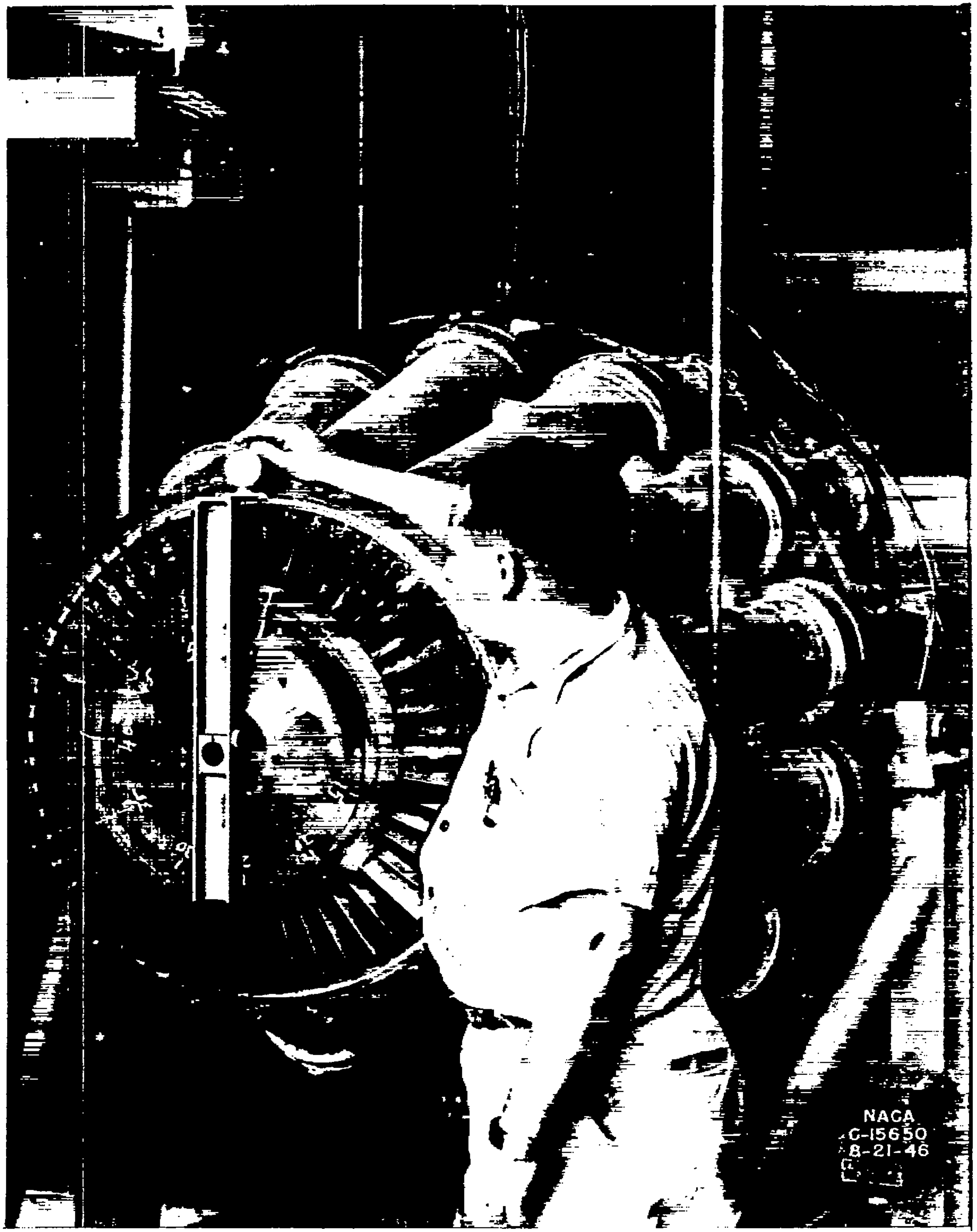
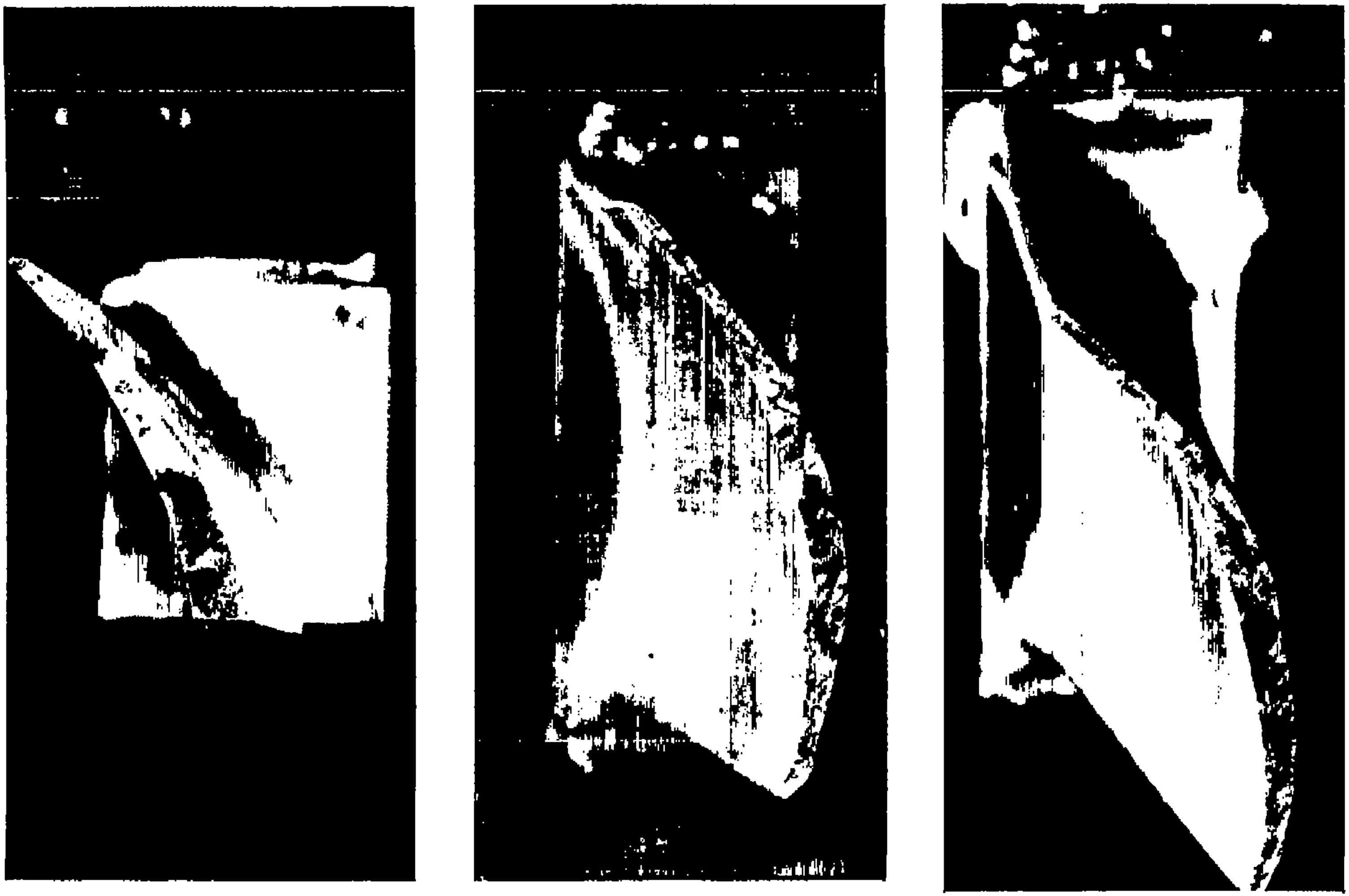



Figure 2. - Turbine-blade measuring jig installed on turbine wheel used to obtain change in position of bucket tips.



Bucket 1-13 Bucket 1-2 Bucket 2-18

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Figure 3. - End views of broken st Vitallium turbine buckets.

Bucket 1-13 Bucket 1-2 Bucket 2-1B

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Figure 4. - Side views of broken cast Vitallium turbine buckets. Buckets were electrolytically etched in 10-percent hydrochloric acid to show grain size.

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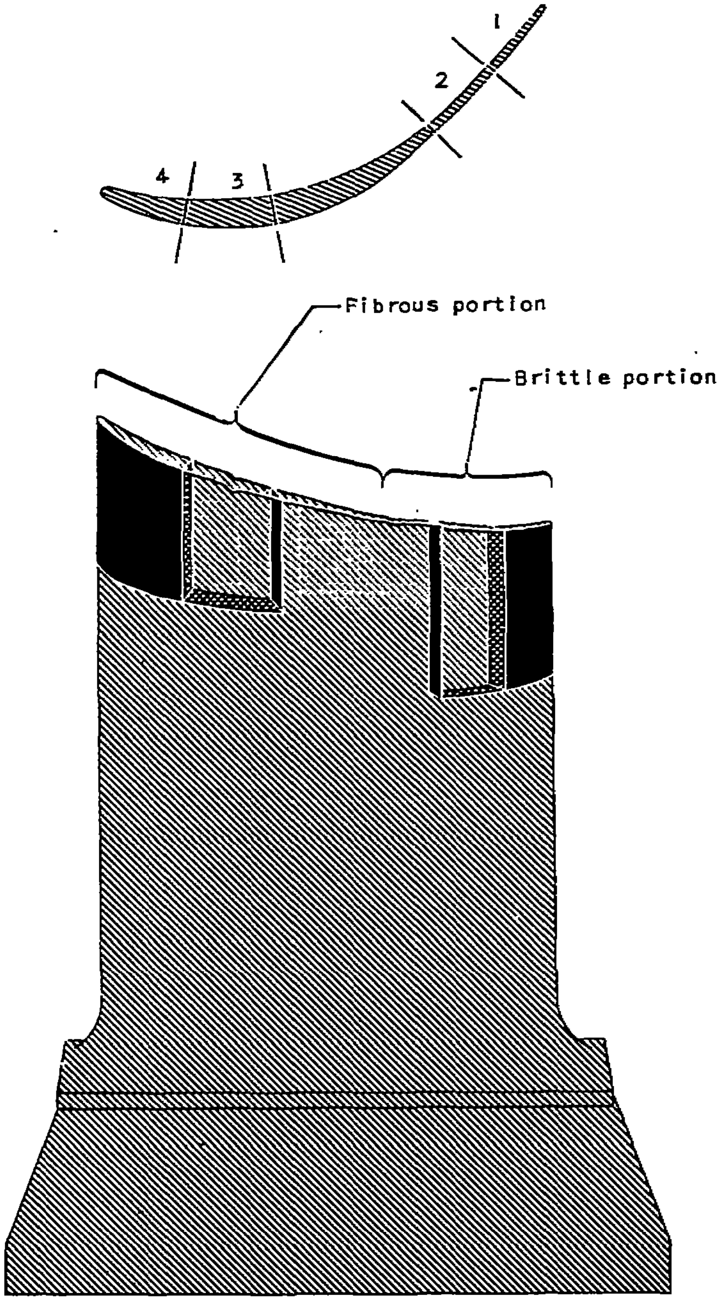


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Figure 5. - Sketch showing location of samples cut from broken turbine buckets for microexamination. Black areas indicate polished surfaces.

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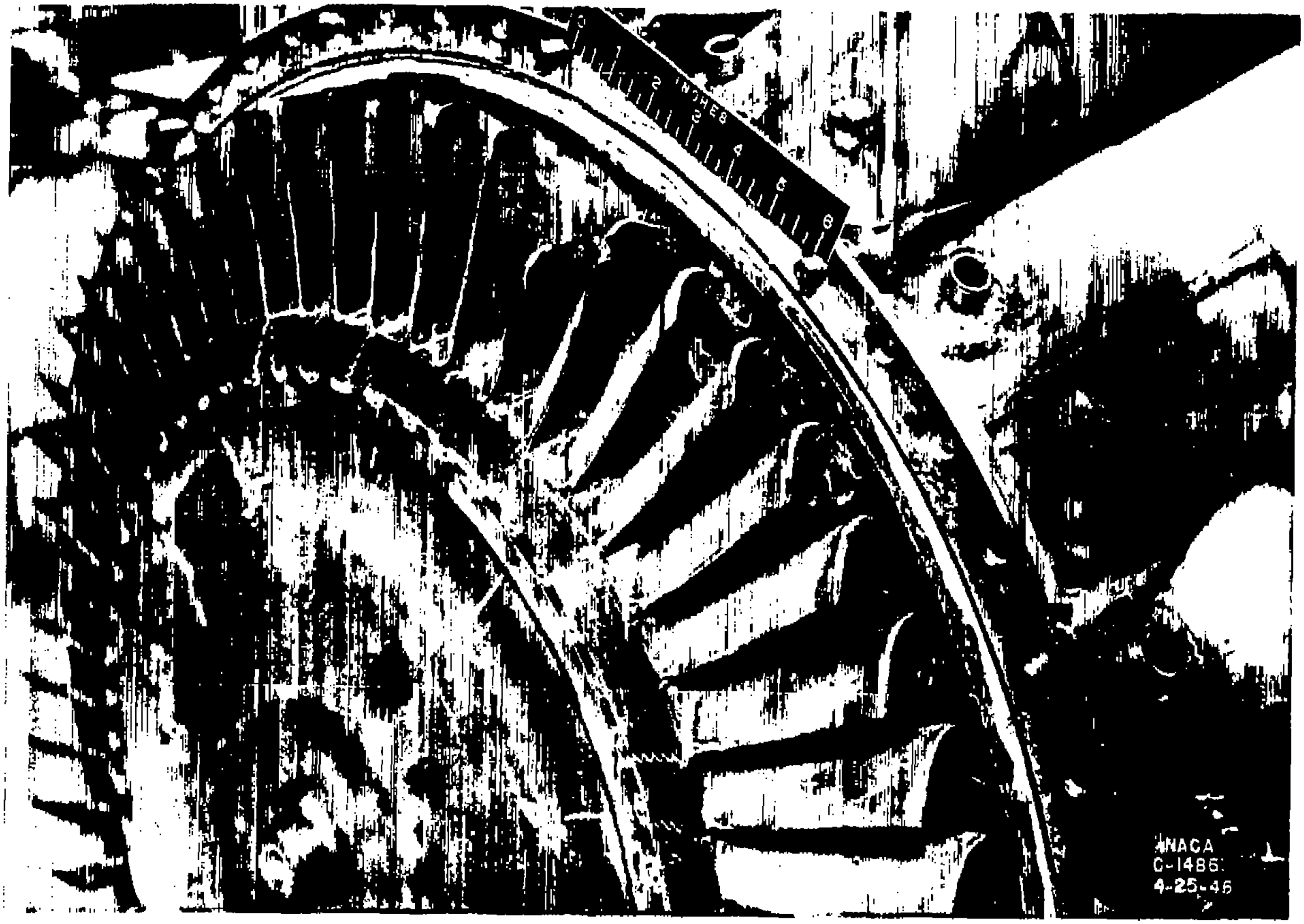


Figure 6. - Wheel I after first bucket failure (bucket I-13), which occurred during cycle 22 (7 hr, 20 min).

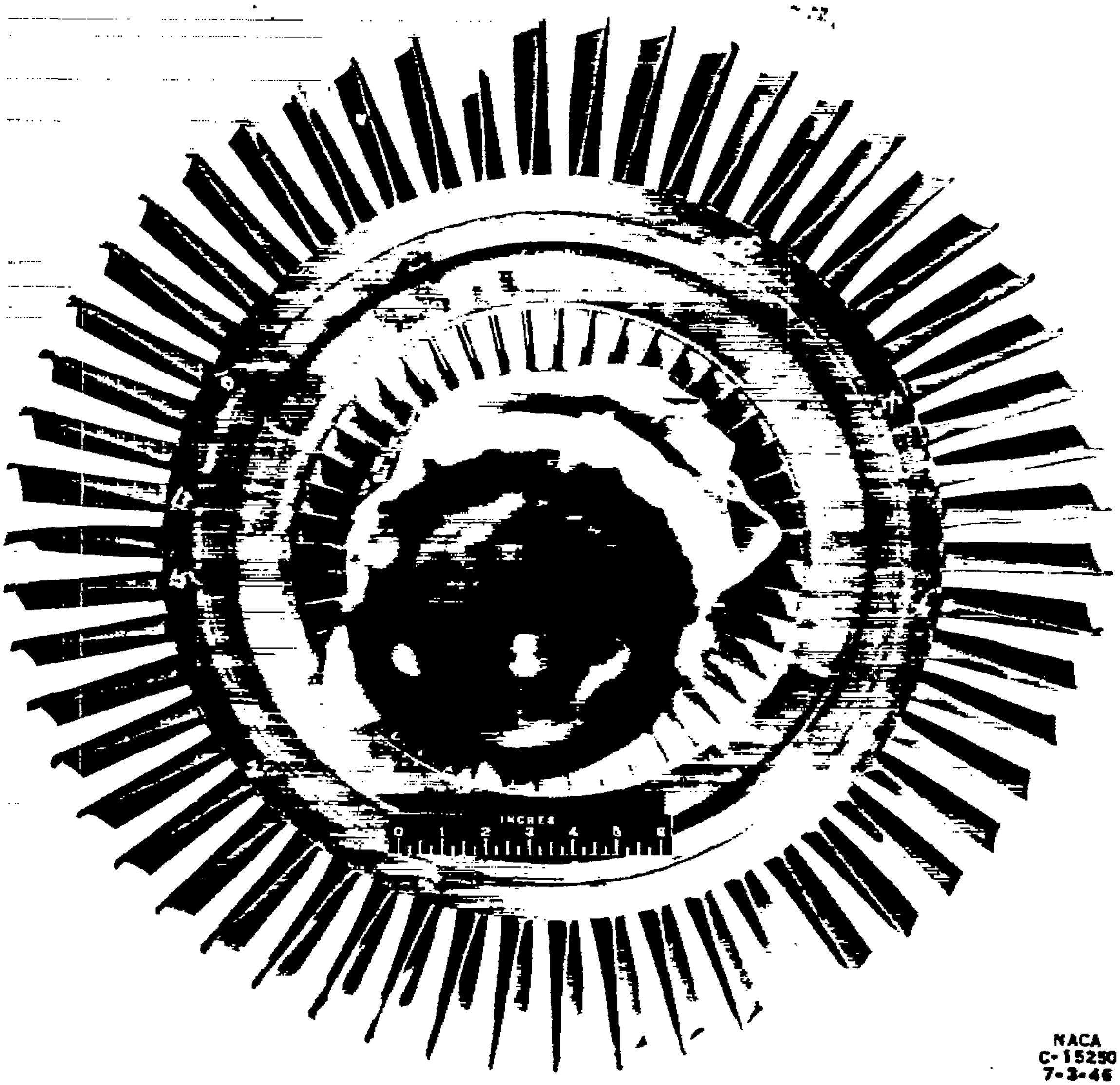


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Figure 7. - Wheel I after second bucket failure (bucket I-2) which occurred during cycle 25 (8 hr, 12 min).


Figure 8. - Wheel 2 after first bucket failure (bucket 2-18), which occurred during cycle 29 (9 hr, 28 min).


Figure 9. - Damaged outer burner tube after 11 hours and 8 minutes.

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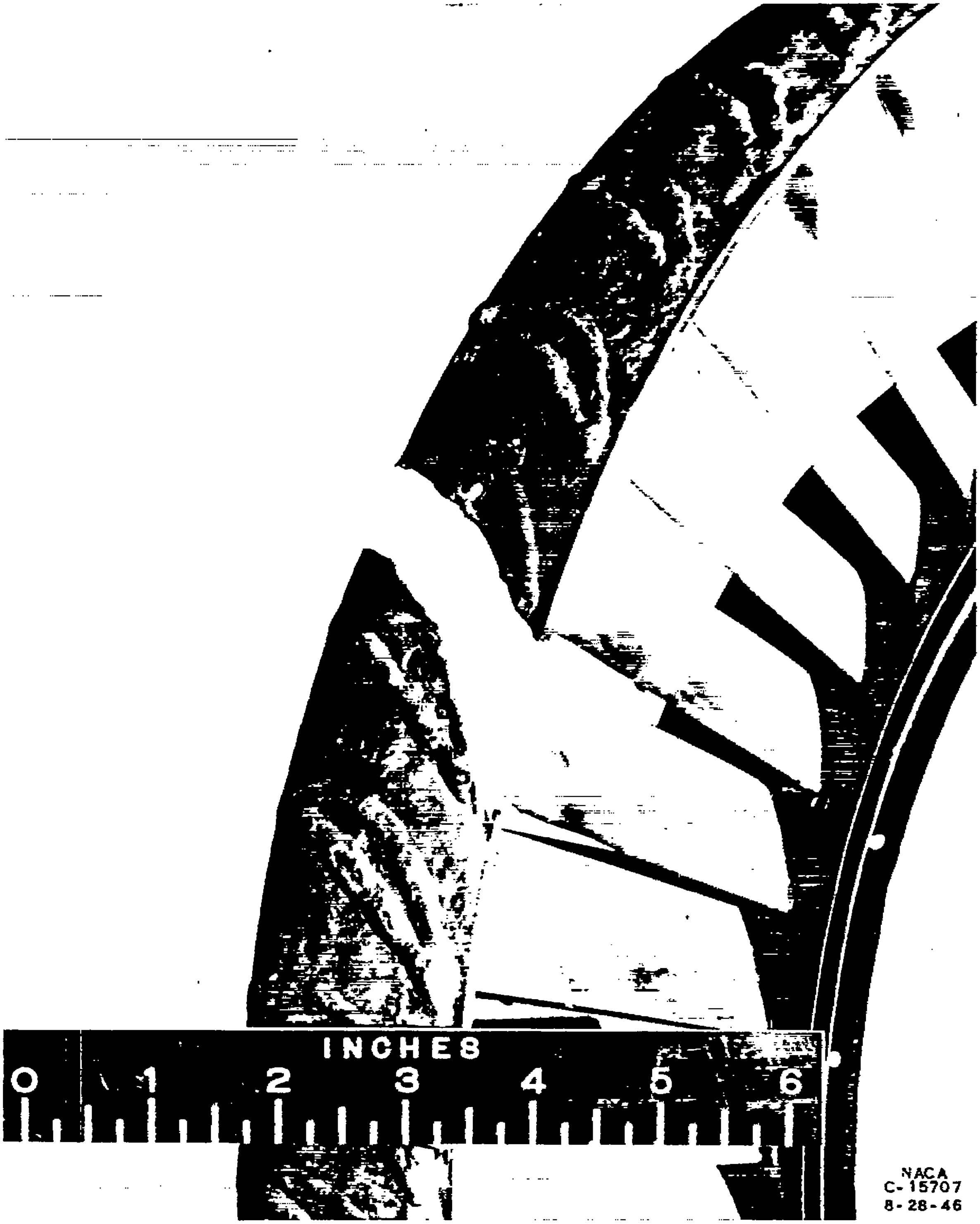


Figure 10. - Damaged turbine-nozzle diaphragm from engine after 28 hours and 44 minutes.

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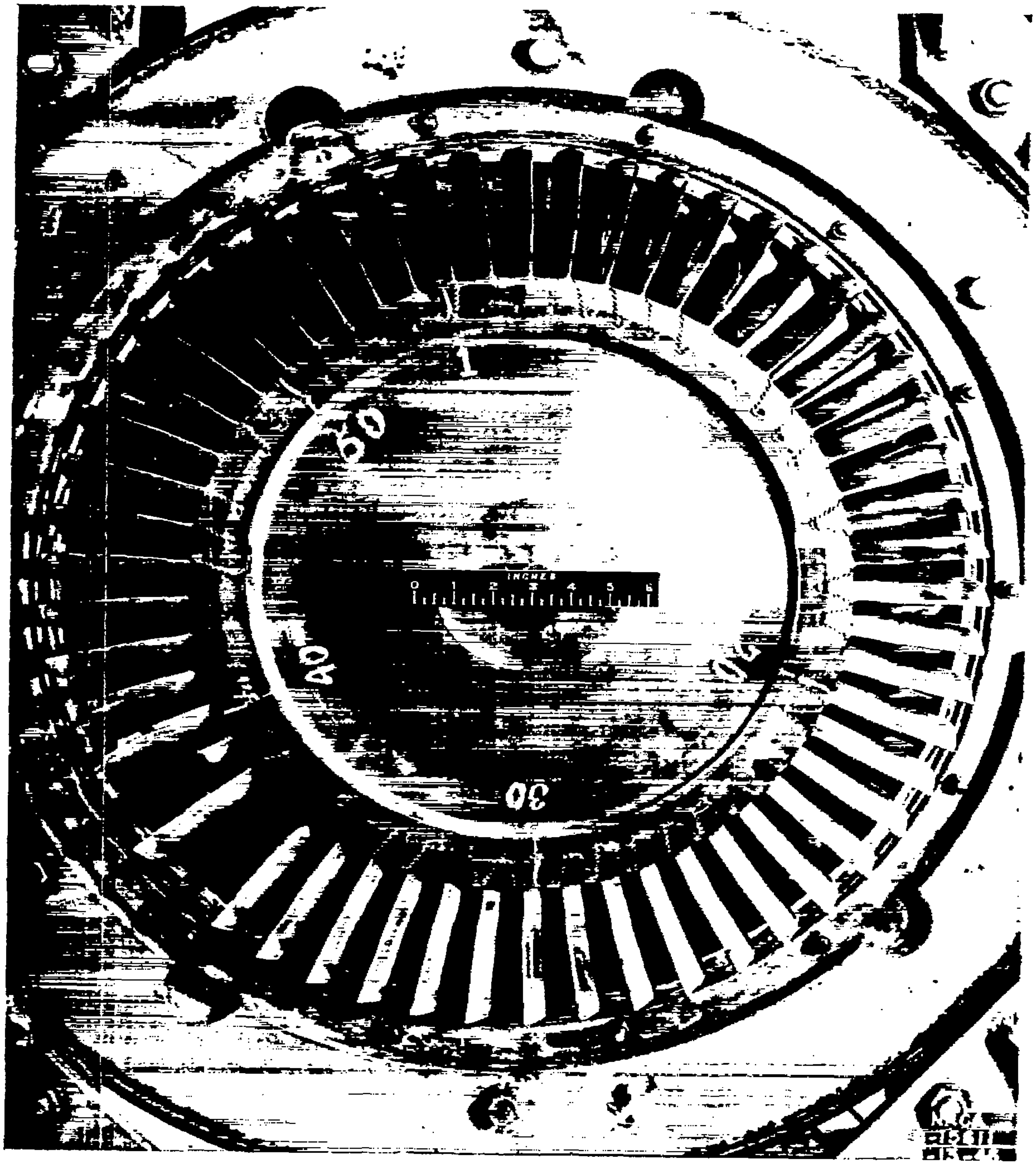


Figure 11. - Wheel 3 after a total running time of 76 hours and 20 minutes showing axial shift of buckets.

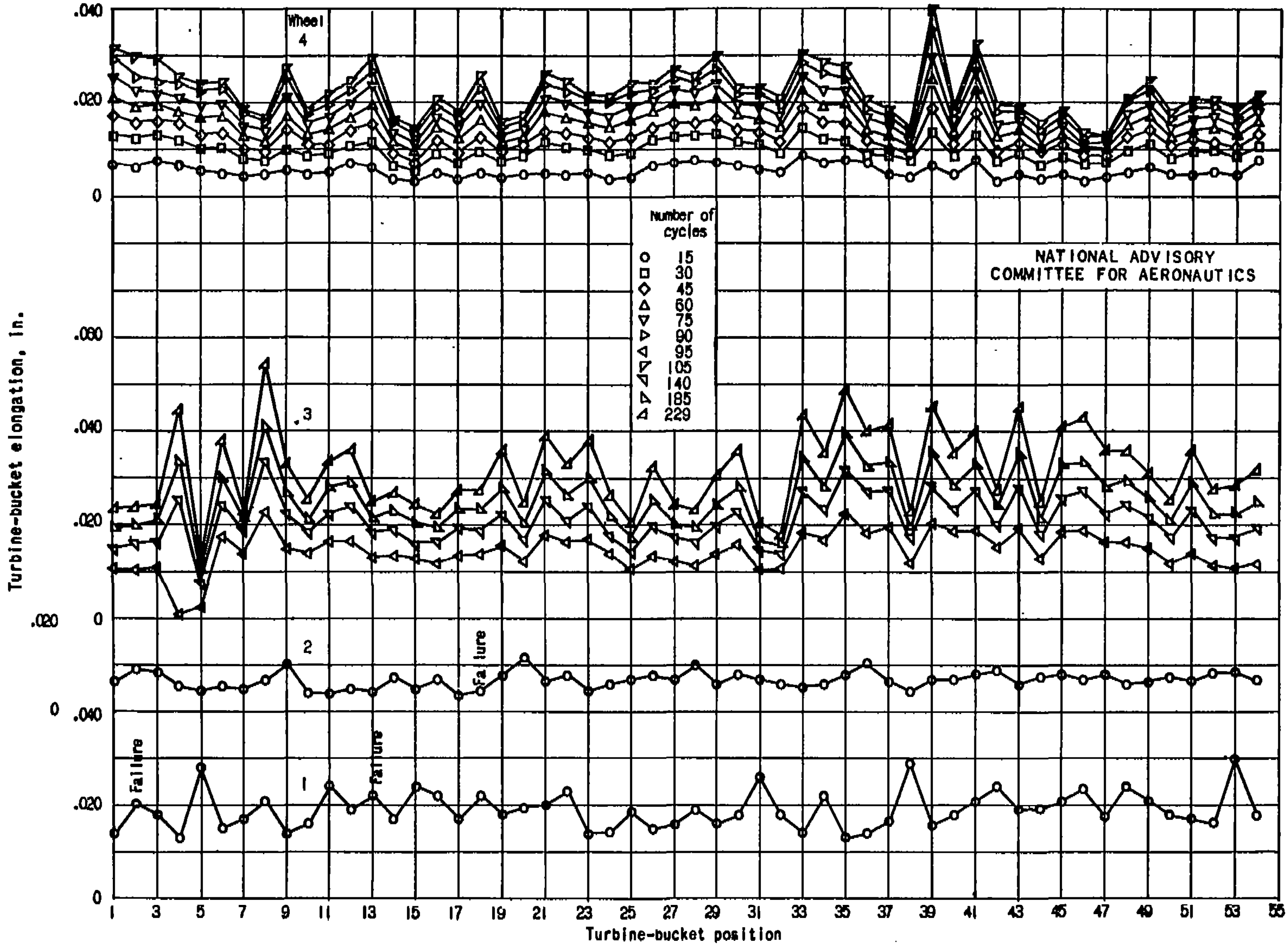


Figure 12. - Variation of turbine-bucket elongation with time for four wheels investigated.

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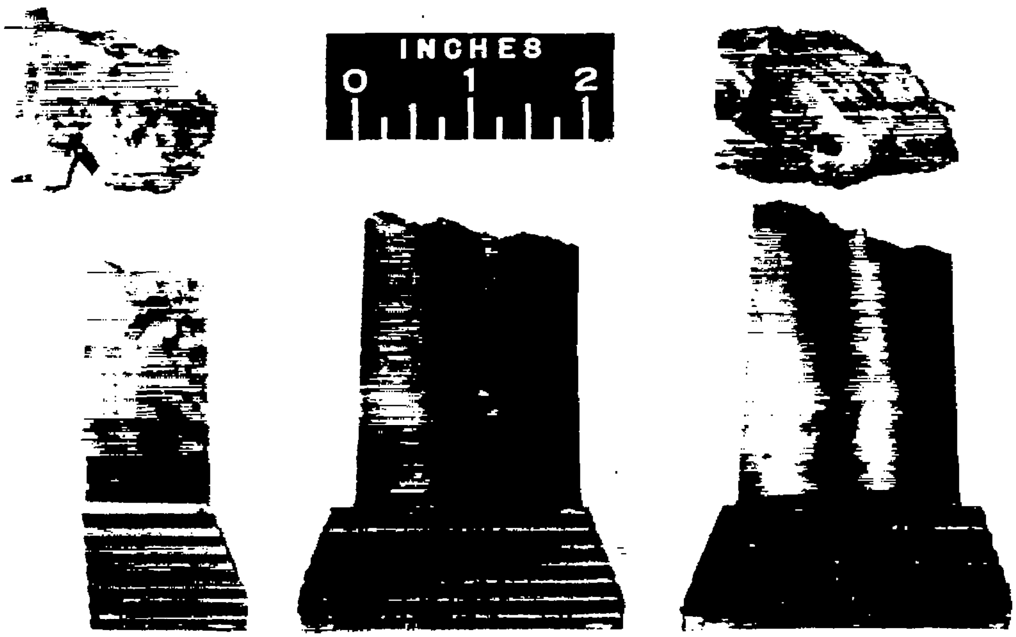


Bucket 1-13 Bucket 1-2 Bucket 2-18

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Figure 13. - Broken cast Vitallium turbine buckets. Bucket 1-13 was sectioned for metallographic examination.

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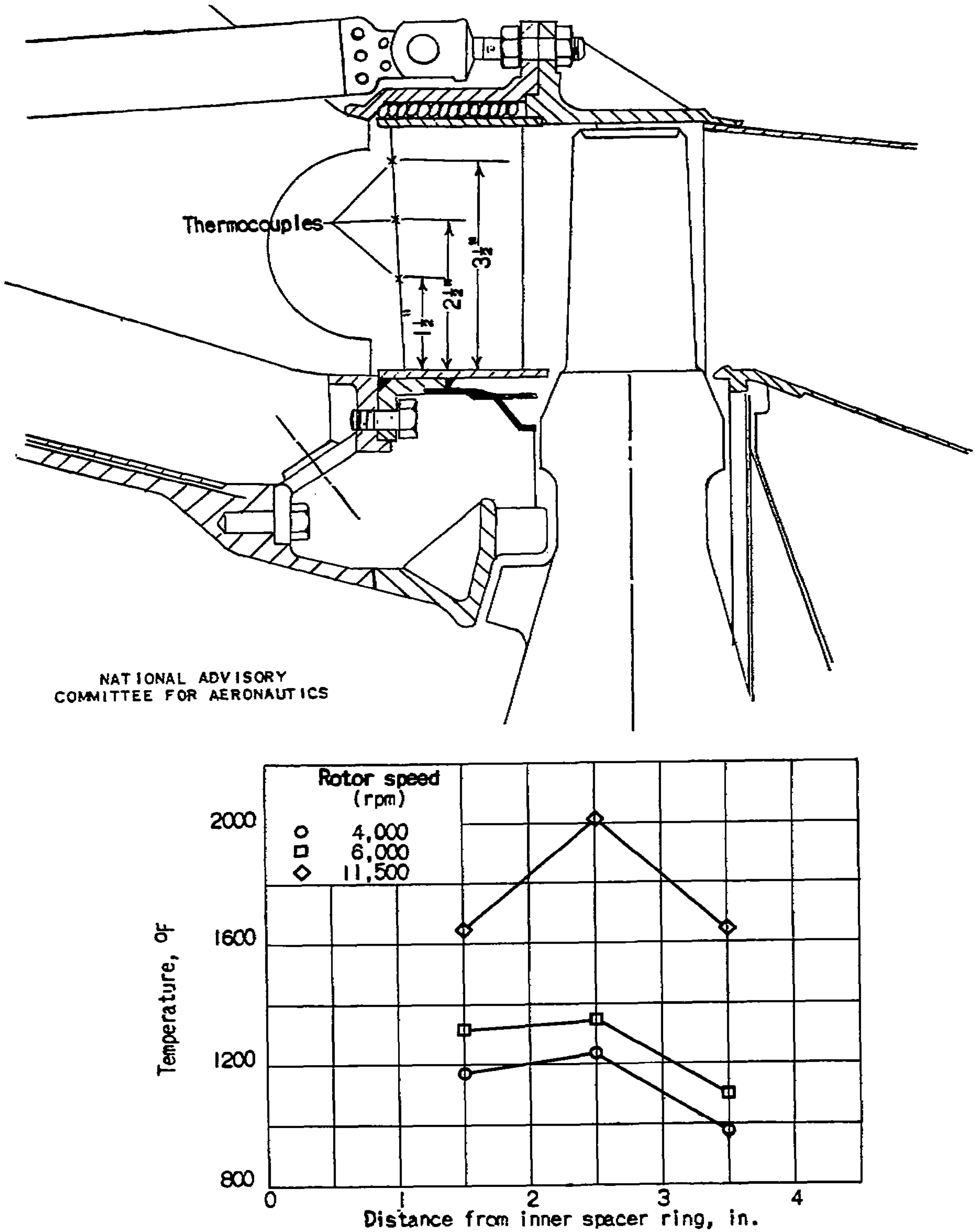


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Figure 14. – Temperature variation along leading edge of turbine-nozzle blade on center line of burner 1 in turbojet engine at various rotor speeds.

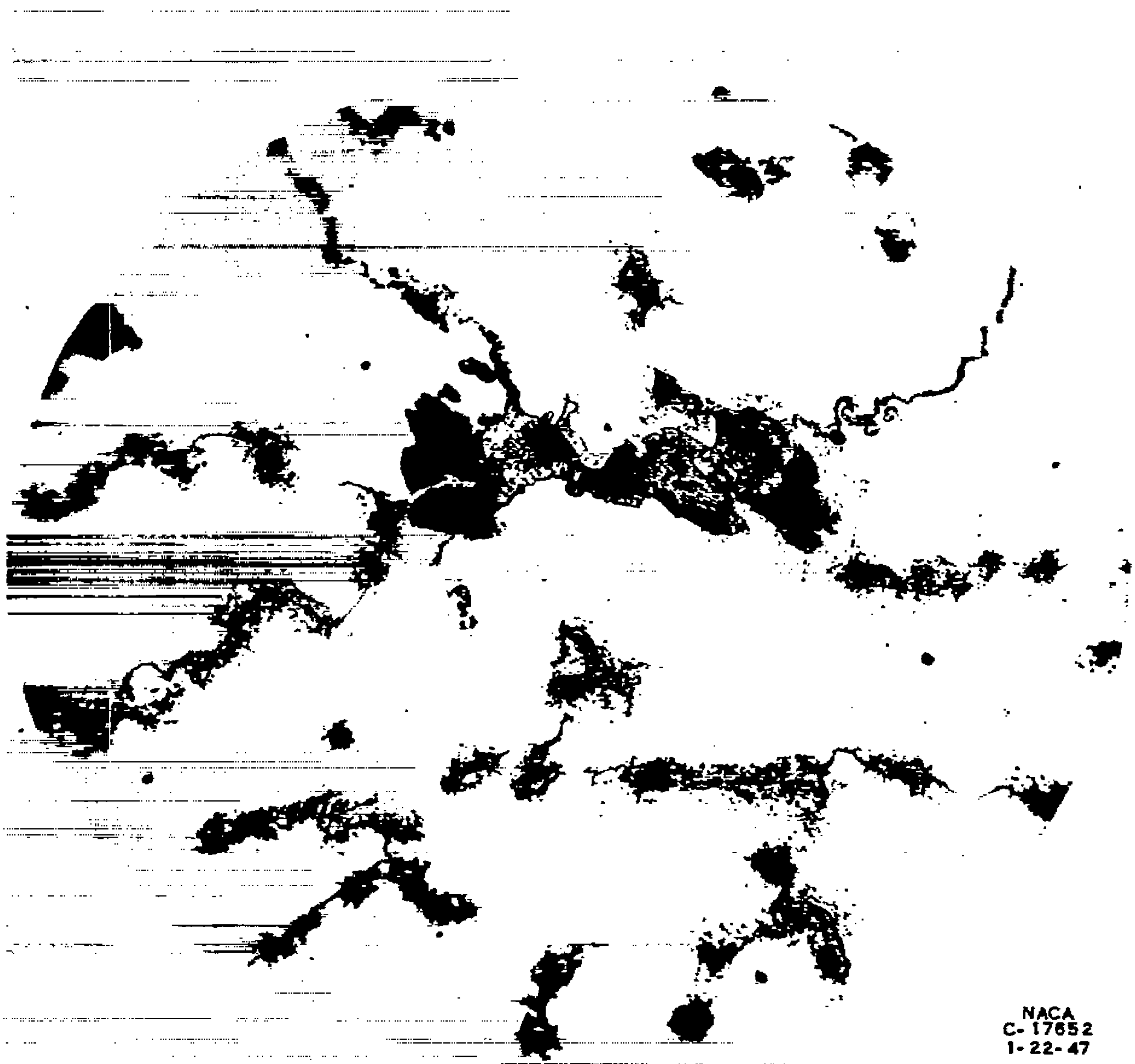


Figure 15. - Microphotograph of sample from location 3 (fig. 5) one-half inch from crack showing eutectic area and precipitated carbides. Aqua-regia etch, 5 percent; magnification, 500X.

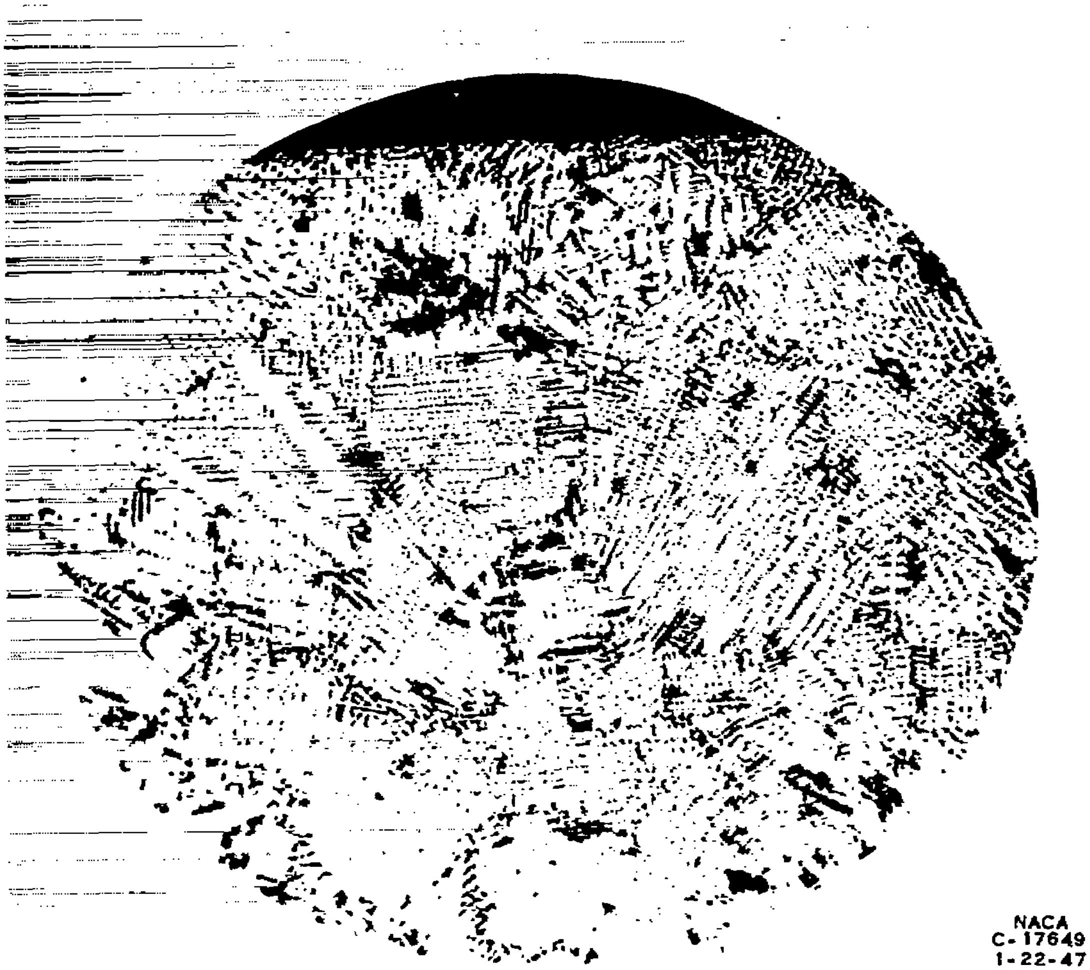


Figure 16. – Microphotograph of sample from location I (fig. 5) close to brittle portion of crack showing large amounts of eutectic material at grain boundaries. Chromic-acid and potassium-permanganate etch; magnification, 50X.


Figure 17. - Microphotograph of sample from location 2 (fig. 5) close to brittle portion of crack showing large amounts of eutectic material at grain boundaries. Aqua-regia etch, 5 percent; magnification, 500X.

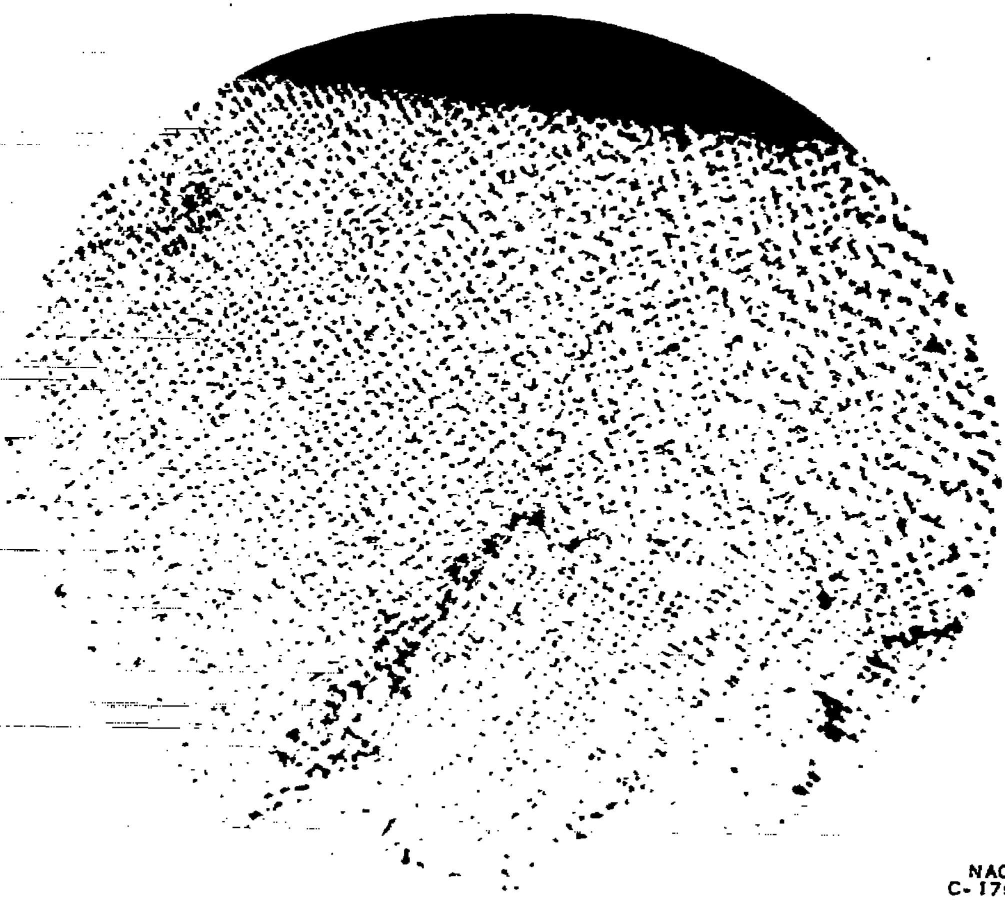

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Figure 18. - Microphotograph of sample from location 4 (fig. 5) at leading edge showing very little amount of eutectic material. Chromic-acid and potassium-permanganate etch; magnification, 50X.